

California Institute of Technology

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"Precision Solar Disk Photometry -- A Tool for Understanding Changes in the Sun's Luminosity"

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Introduction.

The principal scientific aim of this project is to better understand the observed long-term temporal variations in the Sun's luminosity. Satellite observations have revealed that the flux of solar radiation striking the Earth is modulated by the solar magnetic cycle, being approximately 0.1 percent larger during solar maximum. The impact of this irradiance modulation on terrestrial climate is difficult to model. However, the correlation between the Maunder minimum (a period of low solar magnetic activity in the late 1600s) and the "Little Ice Age" in Europe during the same period does suggest that small changes in the solar luminosity can profoundly affect the Earth's climate.

Although direct space-based observations of the total solar irradiance are most useful for climate modeling, such observations span only a very short period of recent history, whereas our records of solar activity extend back in time for several centuries. Thus a better understanding of the solar activity-irradiance connection, while interesting in its own right, should provide for a better past history of the solar irradiance output. Furthermore it may eventually be possible, if we substantially improve our understanding of the solar magnetic dynamo and its resultant luminosity variations, to predict future trends in the solar radiative output.

We are addressing this issue by obtaining precision photometric data at Big Bear Solar Observatory (BBSO) using a specialized instrument, the Solar Disk Photometer (SDP), which was designed for these observations. Our plan was to compare spatially resolved photometric data with unresolved irradiance measurements, to help isolate the different physical contributions to the irradiance variations. We have been operating this instrument continuously since 1993, in order to observe the solar brightness changes as the Sun's magnetic activity level rises from the previous solar minimum.

The largely automated data acquisition with the SDP ran very smoothly during this grant period, and our most recent data clearly show the known variations in solar activity. Since the

instrument is quite old (at least in computer years), we recently upgraded the data analysis software considerably. The data are currently written on 9-track-tapes, which are becoming more and more obsolete with time. These tapes are subsequently read using an old VAX workstation, processed somewhat, and the data then transferred to CDs for further analysis. This allows the use of high-level programming languages, such as MATLAB, for further analysis. We now have a complete set of CDs spanning the period 1993-1999. The instrument was also operated during 2000, but the data have not yet been processed.

Data Analysis and Interpretation.

One of the most important areas we are investigating with this data set is the nature of the "diffuse" component of the solar irradiance variations, and most of our recent data analysis effort has been aimed at this question. It is known that sunspots reduce the solar irradiance, with a large sunspot group producing a temporary decrease of up to 0.3 percent. Averaged over time the irradiance reduction from sunspots alone averages to roughly 0.1 percent between solar minimum and maximum. This is countered by large-scale solar faculae, which increase the average irradiance. The facular contribution is more difficult to model accurately, but averaged over time faculae produce an irradiance increase of roughly 0.1 percent over the solar cycle, essentially balancing the sunspot contribution. Since the observed solar-cycle irradiance variation is about 0.1 percent, sunspots and faculae alone do not seem to explain all the observations. The remaining variations appear to be more diffuse in nature, and are thus difficult to pick out from ordinary solar imaging data.

Active network components may be sufficient to explain the diffuse irradiance component, but large-scale temperature variations in the Sun's active latitudes have also been proposed (for example see Kuhn and Stein, *ApJ* 463, L117 (1996)). We can distinguish between these two models using SDP data by observing the spatial dependence of the brightness variations. Brightness variations from magnetic flux tubes, and thus from solar faculae and active network regions, show a facular contrast function that depends strongly on position relative to the solar limb. Raw temperature variations would show no such limb signature.

In a recent publication (Taylor et al., *Solar Phys.* 178, 1 (1998)) we suggested that the magnetic network hypothesis fit the SDP data better than a simple thermal model, since the brightness variations showed a limb dependence consistent with the magnetic model. However this was based entirely on data taken near solar minimum, so the result could not be very conclusive. We now have data through 1999 analyzed, and the facular-like limb dependence in the photometric data persists. Thus it appears more and more that the luminosity variations arising from active magnetic network elements are responsible for the diffuse component of the solar irradiance variations.

Quantifying these conclusions further has proven most problematic, however. Libbrecht was joined by Martin Woodard from BBSO in analyzing the SDP data, and we found a number of puzzling inconsistencies in the data. We first noticed that the brightness variations recorded with the SDP are approximately a factor of two larger (near the limb) than our old Mt. Wilson limb photometer data (see Kuhn, Libbrecht, and Dicke, Science 242, 908 (1988)), after compensating for solar activity variations. On the other hand, our first SDP data from 1991 were roughly consistent with the Mt. Wilson data. We naturally suspected a software bug, but have been unable to find anything in any of the data sets. Because of these problems we have not been able to come up with an irradiance model that reconciles the (resolved) ground-based data with the satellite irradiance data. Thus we are still short of our primary goal of making an accurate *quantitative* comparison between the SDP data and solar irradiance data. We are currently analyzing the signal from laminar refraction (in the Earth's atmosphere) in the SDP data, to use that as a calibration signal. Relating these data to recent helioseismic results is also being pursued, along with Phil Goode at BBSO.